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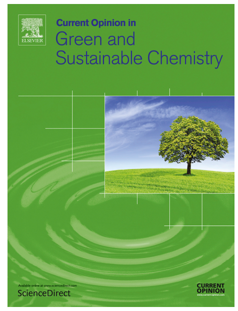

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Facilitating Active Learning within Green Chemistry

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Introduction

Utilization of green chemistry principles is becoming mainstream practice internationally in academic, industrial and governmental environments. In order to aid the transition of society and the economy towards a more sustainable future, the next generation of chemists and chemical engineers must embed green chemistry within their practice. Integration of green chemistry principles can be instigated and enhanced through education at the school, university and graduate/continuing professional development (CPD) levels. For the education to be effective, learners must be engaged with green chemistry at a deep level [1]. One methodology to contribute towards the achievement of such engagement is for facilitators to employ active learning strategies in a range of teaching environments.

Active learning is a teaching strategy whereby learners are actively or experientially participating in the learning process, enabling students to engage in higher order cognitive tasks such as 'analysing' and 'evaluating', resulting in a deeper understanding of subject matter [2]. There are a variety of methodologies that can be implemented to facilitate active learning including project-based learning, inquiry-based learning, experiential learning, just-in-time teaching, contextualised learning and cooperative learning [3]. The aforementioned methodologies are intimately related and often utilised in conjunction, alongside the option for instructors to simultaneously foster social learning experiences by embedding group work throughout the sessions. Use of technology can also be incorporated in order to enhance the learning experience such as by facilitating 'flipped' lectures or provision of interactive online content [4, 5, 6].

Active learning has been applied in multiple environments such as lecture theatres, classrooms, laboratories and online in order to teach green chemistry. This review demonstrates how instructors have achieved this implementation through course design and integrating various methodologies in different environments (see Figure 1 for an overview of the main concepts covered). A particular emphasis is placed on inquiry-based learning where students are provided with a scenario or problem, which challenges them to identify questions and determine associated solutions. Such interventions in green chemistry education reported between 2015 and 2017 are discussed.

Course design to facilitate active learning in green chemistry

A stand-alone undergraduate-level green chemistry course adopting non-traditional teaching techniques has been established at Westminster College in the US [7]. Course teaching methods include: collaborative exploration of case studies and journal articles using open source software to share and group edit work; group concept mapping exercises; student preparation of their own green chemistry educational module; and creation and delivery of a green chemistry laboratory activity for school children adapted from a classical experiment. This particularly dynamic course not only provides students with a thorough understanding of green chemistry, but also encourages them to contribute to the understanding of a wider audience and thus providing additional societal benefit. In a study on the role of a green chemistry curriculum to improve secondary school students understanding of acid-base concepts, Karpudewan et al. [8] report that the students gain a deeper appreciation of the subject when green chemistry concepts are incorporated as they readily make connections with their every-day lives and develop their argumentation skills through being able to debate the impacts of both green and traditional chemistry.

Delivery methodologies:

Inquiry based learning in the laboratory

This category of active learning within the field of green chemistry is without doubt the most prevalent and covers a broad number of subject areas At undergraduate level a balance needs to be struck between delivering training to students in a broad range of basic core technical skills, whilst ensuring that considerations of the impact and sustainability of the research are explored through understanding of green chemistry. Numerous advances in realising this balance have been made recently by Purcell et al. [9], Günter et al. [10], L.P. Novaki et al. [11], Guron et al. [12], Serafin and Priest [13], and Fennie and Roth [14]. Another technique for incorporating green chemistry in a laboratory setting is to compare and contrast classical vs greener methods for the synthesis of a target compound, as adopted by Paluri et al [15]. A Green Reagents and Sustainable Processes (GRASP) substitution approach was employed by Hurst et al. in two experiments to enable students to safely overcome threshold concepts within materials chemistry [16, 17, 18]. (See Table 1 for a detailed description of recent developments at an undergraduate level).

In a high school setting, an experiment to explore the nature of polymers, their application in society and how green chemistry principles can be applied by scientists to design more sustainable materials has been developed by Knutson et al. [19]. Students test the physical and mechanical properties of poly(ε-caprolactone) as a model for medical sutures and then design their own experiment to test the potential for greening sutures by blending with polylactic acid and testing how the properties of the 'suture' are modified. Depending on the level of the students, the activity can be modified to be either fully open inquiry, where students develop their own questions to test, or guided inquiry where groups are assigned a question to address.

Inquiry-based learning in the classroom

Inquiry-based learning also finds application in the classroom. While many of the inquiry-based learning resources use a case study or real world context to provide a scenario for problem solving, Overton and Randles [20] argue that this does not reflect real world problem solving as the problem scenario is static, whereas in real life both the context and scope of the problem can change with time. As part of this work, a new dynamic problem based learning model was devised whereby students tackle an individualised problem. Different groups of students are given different scenarios on sustainable development (including greening transportation), different initial data sets and also during the exercise are provided with additional information that could either positively or negatively impact their problem.

Enriching laboratory-based practicals *via* active learning in the classroom

Laboratory-based learning can be augmented through activity extensions in the classroom. An excellent example of this is provided by Aubrecht et al. [21] in the series of field trips developed for high school students. Seven laboratory activities covering green chemistry, energy production and environmental degradation are supported by a comprehensive range of pre-and post-laboratory classroom activities. Students work in small groups in a 'jigsaw-style' approach; each student in the group is given a different scientific article to read, before discussing as a group how the articles link with one another, what the relationship between the articles and the laboratory activity is and what connection there is to sustainability, before finally recording their consensus. Duarte et al. [22] report another methodology involving creation of a pre-laboratory classroom exercise that encompasses evaluation of the greenness of a variety of alternative literature protocols proposed for a set synthesis (using a metrics tool, Green Star [23]. Following this assessment, students decide which protocol is greenest for each stage (i.e. reaction, isolation and purification) before going on to test this new combined method in the laboratory. This technique encourages students to think critically and challenges the preconception that a set protocol must be used within the laboratory.

Another approach to enrich laboratory-based activities has been conceived by Shamuganathan and Karpudewan [24], who have embedded science writing heuristics (SWH) into green chemistry experiments to gain a higher level of interaction and inquiry into the activity. In classroom exercises, students are required to pose questions and provide methods to address these questions in relation to the laboratory exercises, before carrying out appropriate investigations. By challenging students to think more deeply about the subject through the SWH, the authors found that they demonstrated greater environmental literacy.

A completely different way to improve understanding gained from laboratory practicals has been developed by Rand et al. [25]. Students are directed to create an animated, instructional video posted on YouTube of the acid-rain neutralisation experiment they have carried out, including the laboratory set-up and scientific concepts behind the experiment. As well as promoting a deeper understanding of the science, students also benefit from the opportunity to enhance their communication skills in an engaging and collaborative approach. There is potential for this work to be extended by empowering students to communicate context-based scenarios and green chemistry principles via YouTube for outreach purposes, enabling the students to become global educators in their own right [26].

Hands-on, non-laboratory based learning

Green chemistry metrics can sometimes present challenges to students with regard to comprehending the difference between the multitude of various equations available, the different parameters included in each and what the calculated figure represents. Hudson et al. [27] have devised a hands-on method for understanding different mass-based metrics and assessing their strengths and weaknesses through modelling reactions using interlocking building blocks. The use of these bricks facilitates an effective and versatile method of visualising whole molecules, individual atoms and mass, as well as allowing students to readily make the connection between exactly what is converted to product and what is classified as waste or by-product. Similarly, Enthaler [28] uses interlocking building blocks to aid visual understanding of the synthesis of plastics from monomers and discuss end-of-life options for plastics including polymer recycling (chemical and mechanical) energy recovery and landfill. The visual and interactive elements of this methodology allow the concepts to be readily grasped and hence are ideal for demonstration to a lay audience.

Online learning

Another remarkably simple but effective method for incorporating online elements into active learning of green chemistry is reported by Henry [29]. As opposed to providing students with completed class notes or truncated notes to be completed through listening to the lecture, key word created class notes (KWCCNs) were generated via an interactive approach whereby students worked together to locate information on the web prompted by a key word and reference to particular websites.

Online learning can also be used outside of an academic setting. As it is flexible enough to be compatible with learners in full time employment who may have restrictions on their time commitments, online learning is a tool that can be readily adopted within industry for CPD purposes. Online learning, however, is not necessarily active, unless it incorporates elements of interactivity as described above or other methodologies that encourage more in-depth interaction with the material therein other than simply reading or viewing it. The CHEM21 online learning platform [30, 31], established by the EU IMI CHEM21 project (Chemical Manufacturing Methods for the 21st Century Chemical Industries), was specifically designed to provide a broad range of free, shareable and interactive educational and training materials to promote the uptake of green and sustainable methodologies in the synthesis of pharmaceuticals. Interactive elements include multiple choice quizzes with instant feedback, and downloadable problem-solving exercises (that can be carried out individually or in groups in a workshop setting) to encourage critical thinking on topics such as metrics [32], solvent selection [33] and process safety [34].

Active learning in assessment

As well as devising an organic chemistry laboratory course incorporating green chemistry, Beltman et al. [35] have embedded additional valuable skills in the course in the form of preparation of scientific manuscripts from the results of the practical, thus developing the students' writing and editing abilities, and critically reviewing the manuscripts of their peers and assessing them using a specified rubric. Over a series of weekly practical classes working in alternating pairs, all students are given the opportunity both to write and review manuscripts.

Conclusions

Active learning is a highly effective way to teach green chemistry, as it successfully promotes critical thinking - an essential aspect in embedding green chemistry into every day practice. Through incorporating green chemistry thinking into all areas of chemistry, an additional benefit can be realised i.e. circumvention of the common misconception that green chemistry is a separate branch of chemistry. Significant scope remains to develop interventions that combine multiple active learning strategies, particularly at the school level where current work at the University of York is focused on developing new multimedia resources in green chemistry using a 'students as partners' approach. Finally, the efficacy of such innovations should be evaluated in, ideally, a quantitative fashion to measure the success of the learning experience.

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Encouraging critical thinking in students through pre-experimental desk-based evaluation of a range of different methodologies for a synthesis using a metrics tool to ultimately decide upon the greenest combination.

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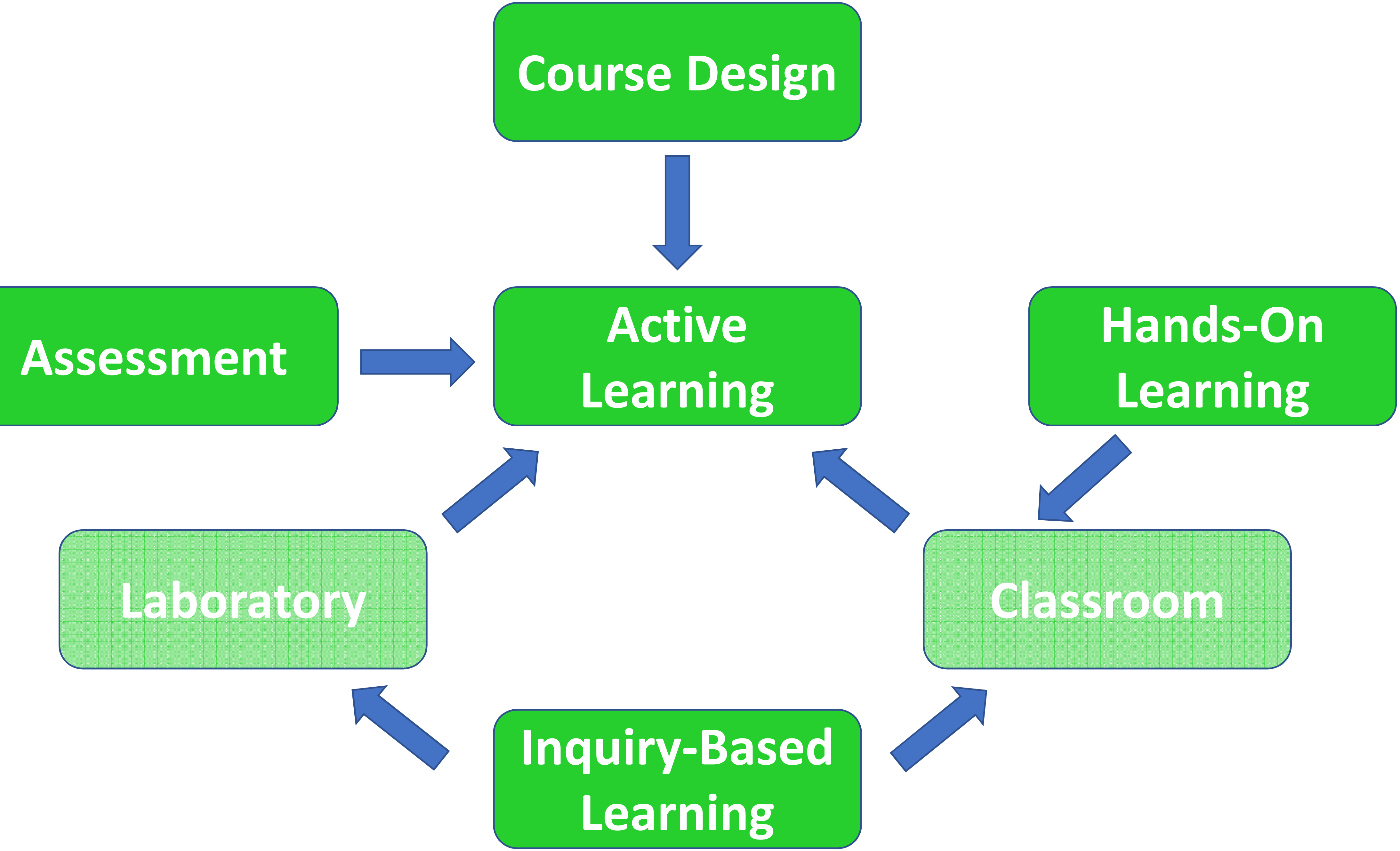
The creation of a suite of organic chemistry laboratory sessions with inherent embedded green chemistry content was further enhanced through incorporation of authoring and reviewing scientific manuscripts based on experimental results and peer assessment thereof.

Target Area	**Specific Topic(s) Covered**	**Methodology**
Analytical Chemistry	Assessment of the antibacterial properties of thyme leaf extracts	Students formulate and test their own hypotheses over a number of weeks in a series of research-like experiments that impart knowledge and understanding of green chemistry, such as solvent choice, use of renewables and consideration of waste streams [9].
Analytical Chemistry	Qualitative and quantitative analysis of cations	Five different real-world scenarios, including a real chemical incident and a fireworks display, are integrated into experiments and embed topics such as green chemistry principles, sustainability and the effects of heavy metals on human health and the environment requiring students to define the problem, produce their own hypothesis and design their own analyses to reach a solution. [10].
Analytical Chemistry	Quantitative analysis of gasoline blends	Students are involved in decision making for a laboratory protocol examining the use of green dyes for assessing bio-ethanol-gasoline blends [11].
Inorganic Chemistry	Coordination compound chemistry	Incorporation of life-cycle thinking with a particular emphasis on chemical safety and chemical waste, both in terms of human health and environmental implications. Students include a sustainability section in laboratory reports and devise their own changes to improve the sustainability of the original laboratory procedure based on safety information [12].
Organic Chemistry	Passerini reactions	Addition of a puzzle element through incorporation of structure elucidation exercises as a guided enquiry activity to be worked on in teams [13].
Organic Chemistry	Amide-bond forming reactions	Experimental data obtained is used to make direct comparisons *via* metrics assessment on each method to decide upon the greenest mode of synthesis. Students are also required to consider the usefulness of each of the metrics and propose hypothetical ways to further improve the green credentials of amide-bond formation [14].
Organic Chemistry	Synthesis of noble metal nanoparticles (NPs).	Students first follow a standard procedure to synthesise conventional noble metal NPs before researching, proposing and then carrying out a greener synthesis using environmentally friendly reducing agents [15].
Materials Chemistry	Properties of gels	The typical methodology [16] of examining rheological properties of poly(vinyl alcohol) gels crosslinked with borax (suspected of damaging fertility and the unborn child), is replaced with evaluation of the non-Newtonian properties of a green calcium-crosslinked-alginate gel (basically seaweed) [17]. Evaluation of a range of properties of smart polymers is also reported utilizing a green genipin-crosslinked chitosan network in contrast to the more commonly used glutaraldehyde/formaldehyde/epoxy compound-based alternatives [18].

Table 1: Recent advances in green chemistry related inquiry based learning in the undergraduate laboratory.


Course Design
Assessment
Active Learning
Hands-On Learning
Laboratory
Classroom
Inquiry-Based Learning

Highlights

1. Active learning is participatory and contributes towards deep subject understanding.

2. Applications of active learning strategies to green chemistry teaching are detailed.

3. Inquiry-based and hands-on learning are the most prevalent strategies used.

4. Scope for facilitators to take a more combinatorial approach to session design.

5. The number of interventions at school level could be further developed.